Quantum Theory Needs No 'Interpretation'

Christopher A. Fuchs and Asher Peres

Recently there has been a spate of articles, reviews, and letters in PHYSICS TODAY promoting various "interpretations" of quantum theory (see March 1998, page 42; April 1998, page 38; February 1999, page 11; July 1999, page 51; and August 1999, page 26). Their running theme is that from the time of quantum theory's emergence until the discovery of a particular interpretation, the theory was in a crisis because its foundations were unsatisfactory or even inconsistent. We are seriously concerned that the airing of these opinions may lead some readers to a distorted view of the validity of standard quantum mechanics. If quantum theory had been in a crisis, experimenters would have informed us long ago!

Our purpose here is to explain the internal consistency of an "interpretation without interpretation" for quantum mechanics. Nothing more is needed for using the theory and understanding its nature. To begin, let us examine the role of experiment in science. An experiment is an active intervention into the course of Nature: We set up this or that experiment to see how Nature reacts. We have learned something new when we can distill from the accumulated data a compact description of all that was seen and an indication of which further experiments will corroborate that description. This is what science is about. If, from such a description, we can *further* distill a model of a free-standing "reality" independent of our interventions, then so much the better. Classical physics is the ultimate example of such a model. However, there is no logical necessity for a realistic worldview to always be obtainable. If the world is such that we can never identify a reality independent of our experimental activity, then we must be prepared for that, too.

The thread common to all the nonstandard "interpretations" is the desire to create a new theory with features that correspond to some reality independent of our potential experiments. But, trying to fulfill a classical worldview by encumbering quantum mechanics with hidden variables, multiple worlds, consistency rules, or spontaneous collapse, without any improvement in its predictive power, only gives the illusion of a better understanding. Contrary to those desires, quantum theory does *not* describe physical reality. What it does is provide an algorithm for computing *probabilities* for the macroscopic events ("detector clicks") that are the consequences of our experimental interventions. This strict definition of the scope of quantum theory is the only interpretation ever needed, whether by experimenters or theorists.

Quantum probabilities, like all probabilities, are computed by using any available information. This can include, but is not limited to information about a system's preparation. The mathematical instrument for turning the information into statistical predictions is the probability rule postulated by Max Born.[1] The conclusiveness of Born's rule is known today to follow from a theorem due to Andrew Gleason.[2] It is enough to assume that yes–no tests on a physical system are represented by projection operators P, and that probabilities are additive over orthogonal projectors. Then there exists a density matrix ρ describing the system such that the probability of a "yes" answer is $\mathrm{tr}(\rho P)$. The compendium of probabilities represented by the "quantum state" ρ captures everything that can meaningfully be said about a physical system.

Here, it is essential to understand that the validity of the statistical nature of quantum theory is not restricted to situations where there are a large number of similar systems. Statistical predictions do apply to single events. When we are told that the probability of precipitation tomorrow is 35%, there is only one tomorrow. This tells us that it is advisable to carry an umbrella. Probability theory is simply the quantitative formulation of how to make rational decisions in the face of uncertainty.

We do not deny the possible existence of an objective reality independent of what observers perceive. In particular, there is an "effective" reality in the limiting case of macroscopic phenomena like detector clicks or planetary motion: Any observer who happens to be present would acknowledge the objective occurrence of these events. However, such a macroscopic description ignores most degrees of freedom of the system and is necessarily incomplete. Can there also be a "microscopic reality" where every detail is completely described? No description of that kind can be given by quantum theory, nor by any other reasonable theory. John Bell formally showed[3] that any objective theory giving experimental predictions identical to those of quantum theory would necessarily be nonlocal. It would eventually have to encompass everything in the universe, including ourselves, and lead to bizarre self-referential logical paradoxes. The latter are not in the realm of physics; experimental physicists never need bother with them.

We have experimental evidence that quantum theory is successful in the range from 10^{-10} to 10^{15} atomic radii; we have no evidence that it is universally valid. Yet, it is legitimate to attempt to extrapolate the theory beyond its present range, for instance, when we probe particle interactions at superhigh energies, or in astrophysical systems, including the entire universe. Indeed, a common question is whether the universe has a wavefunction. There are two ways to understand this. If this "wavefunction of the universe" has to give a complete description of everything, including ourselves, we again get the same meaningless paradoxes. On the other hand, if we consider just a few collective degrees of freedom, such as the radius of the universe, its mean density, total baryon number, and so on, we can apply quantum theory only to these degrees of freedom, which do not include ourselves and other insignificant details. This is not essentially

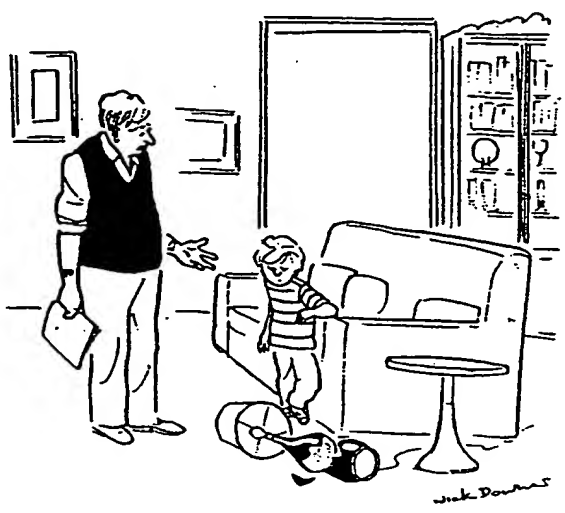
CHRIS FUCHS, *previously the Lee DuBridge Prize Postdoctoral Fellow at Caltech, is now a Director-Funded Fellow at Los Alamos National Laboratory. His daytime research focuses on quantum information theory and quantum computation.* ASHER PERES *is the Gerard Swope Distinguished Professor of Physics at Technion—Israel Institute of Technology, in Haifa, Israel. He is the author of* Quantum Theory: Concepts and Methods *(Kluwer, Dordrecht, 1995).*

different from quantizing t' … netic flux and the electric cu …t in a SQUID while ignoring the atomic details. For sure, we can manipulate a SQUID more easily than we can manipulate the radius of the universe, but there is no difference in principle.

Does quantum mechanics apply to the observer? Why would it not? To be quantum mechanical is simply to be amenable to a quantum description. Nothing in principle prevents us from quantizing a colleague, say. Let us examine a concrete example: The observer is Cathy (an experimental physicist) who enters her laboratory and sends a photon through a beam splitter. If one of her detectors is activated, it opens a box containing a piece of cake; the other detector opens a box with a piece of fruit. Cathy's friend Erwin (a theorist) stays outside the laboratory and computes Cathy's wavefunction. According to him, she is in a 50/50 superposition of states with some cake or some fruit in her stomach. There is nothing wrong with that; this only represents his knowledge of Cathy. She knows better. As soon as one detector was activated, her wavefunction collapsed. Of course, nothing dramatic happened to her. She just acquired the knowledge of the kind of food she could eat. Some time later, Erwin peeks into the laboratory: Thereby he acquires new knowledge, and the wavefunction he uses to describe Cathy changes. From this example, it is clear that a wavefunction is only a mathematical expression for evaluating probabilities and depends on the knowledge of whoever is doing the computing.

Cathy's story inevitably raises the issue of reversibility; after all, quantum dynamics is time-symmetric. Can Erwin undo the process if he has *not yet* observed Cathy? In principle he can, because the only information Erwin possesses is about the consequences of his potential experiments, not about what is "really there." If Erwin has performed no observation, then there is no reason he cannot reverse Cathy's digestion and memories. Of course, for that he would need complete control of all the microscopic degrees of freedom of Cathy and her laboratory, but that is a practical problem, not a fundamental one.

The peculiar nature of a quantum state as representing information is strikingly illustrated by the quantum teleportation process.[4] In order teleport a quantum state from one photon to another, the sender (Alice) and the receiver (Bob) need to divide between them a pair of photons in a standard entangled state. The experiment begins when Alice receives another photon whose polarization state is unknown to her but known to a third-party preparer. She performs a measurement on her two photons—one from the original, entangled pair and the other in a state unknown to her—and then sends Bob a classical message of only two bits, instructing him how to reproduce that unknown state on his photon. This economy of transmission appears remarkable, because to completely specify the state of a photon, namely one point in the Poincaré sphere, we need an infinity of bits. However, this complete specification is *not* what is transferred. The two bits of classical information serve only to convert the preparer's information, from a description of the original photon to a description of the one in Bob's possession. The communication resource used up for doing that is the correlated pair that was shared by Alice and Bob.



"What do you mean, 'a quantum fluctuation?' Didn't we discuss cause and effect?"

It is curious that some well-intentioned theorists are willing to abandon the objective nature of physical "observables," and yet wish to retain the abstract quantum state as a surrogate reality. There is a temptation to believe that every quantum system has a wavefunction, even if the wavefunction is not explicitly known. Apparently, the root of this temptation is that in classical mechanics *phase space* points correspond to objective data, whereas in quantum mechanics *Hilbert space* points corre- …d to quantum states. This analogy is misleading: Attributing reality to quantum states leads to a host of "quantum paradoxes." These are due solely to an incorrect interpretation of quantum theory. When correctly used, quantum theory never yields two contradictory answers to a well-posed question. In particular, no wavefunction exists either before or after we conduct an experiment. Just as classical cosmologists got used to the idea that there is no "time" before the big bang or after the big crunch, so too must we be careful about using "before" and "after" in the quantum context.

Quantum theory has been accused of incompleteness because it cannot answer some questions that appear reasonable from the classical point of view. For example, there is no way to ascertain whether a single system is in a pure state or is part of an entangled composite system. Furthermore, there is no dynamical description for the "collapse" of the wavefunction. In both cases the theory gives no answer because the wavefunction is not an objective entity. Collapse is something that happens in our description of the system, not to the system itself. Likewise, the time dependence of the wavefunction does not represent the evolution of a physical system. It only gives the evolution of our probabilities for the outcomes of potential experiments on that system. This is the only meaning of the wavefunction.

All this said, we would be the last to claim that the foundations of quantum theory are not worth further scrutiny. For instance, it is interesting to search for minimal sets of *physical* assumptions that give rise to the theory. Also, it is not yet understood how to combine quantum mechanics with gravitation, and there may well be important insight to be gleaned there. However, to make quantum mechanics a useful guide to the phenomena around us, we need nothing more than the fully consistent theory we already have. Quantum theory needs no "interpretation."

References

1. M. Born, Zeits. Phys. **37**, 863 (1926); **38**, 803 (1926).
2. A. M. Gleason, J. Math. Mech. **6**, 885 (1957).
3. J. S. Bell, Physics **1**, 195 (1964).
4. C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, and W. K. Wootters, Phys. Rev. Letters **70**, 1895 (1993). ■